The quasar Q0957+561: Lensed CO emission from a disk at z∼1.4?

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In recent years large efforts have been made to detect molecular gas towards high redshifted objects. Up to now the literature reports on only two cases of CO-detection in quasars at a redshift between 1 and 2 – Q0957+561, a gravitationally lensed system at $z = 1.41$ (Planesas et al. 1999) , and HR10 at $z = 1.44$ (Andreani et al. 2000). According to Planesas et al. (1999), ^{12}CO(2→1) emission was detected towards both the lensed images of Q0957+561 with the IRAM Plateau de Bure Interferometer (PdBI; Fig. 1). In contrast to the optical spectra of the two images which support the idea that they are images of one and the same object, the CO-spectra were surprisingly different: the southern image (named CO-B) shows a single blueshifted line whereas a double-peaked line profile with a blue- and a redshifted part appears towards the northern image (CO-A). Based on the observations and on simulations with a gravitational lens program, we are tempted to argue that the line profile traces the presence of molecular gas of a disk in the host galaxy around the quasar. We have now new observations with the PdBI providing the necessary sensitivity to corroborate our disk model.

1 Introduction

Since the discovery of Q0957+561, the first confirmed gravitationally lensed quasar (Walsh et al. 1979) at a redshift of $z = 1.4$, several models have been developed to understand the lensing potential of the intervening galaxies: a giant elliptical galaxy (G1) at a redshift of $z = 0.36$ with a surrounding cluster at $z = 0.355$ and probably another group of background galaxies at $z = 0.5$ (e.g. Angonin-Willaime et al. 1994). Planesas et al. (1999, in the following P99) have recently achieved in observing the CO(2-1) line in Q0957+561, but lacked sensitivity and a detailed lensing model to interpret the origin of the molecular emission. To confirm and substantiate this line profile, we have carried out new observations with the IRAM interferometer making Q0957+561 potentially very valuable for understanding the evolution

of quasars at redshifts $1 < z < 2$. To further improve on P99's interpretation, we have developed a numerical code incorporating existing lensing models of Q0957+561.

2 Observations

CO(2-1) and (5-4) observations of Q0957+561 were done simultaneously in 1998 and again in 2003 with the IRAM interferometer.
Continuum emission: In the 3.1mm radio continuum, two lensed images of the quasar, labeled A and B (pointlike), and a radio jet C (extended) appear at this wavelength (Fig. 1), in agreement with VLA observations (Harvanek et al. 1997). The positions coincide with the optical ones within the errors. There is no evidence for variability above 10% between May 1998 and April 2003 in all three components. The lack of any clear detection at 1.3mm could also be a sign for resolving out flux in the smaller beam.
Line emission: After subtracting the continuum the integrated CO(2-1) map shows two lensed images labeled CO−A and CO−B, as in P99. The emission centroids of the two images are separated by $\sim 1''$ more than in the optical/radio. The two CO line components show different spectral profiles. A double-peaked profile is visible towards the northern image CO−A whereas only a single (blueshifted) velocity component is detected towards CO−B. No line emission was detected towards CO(5-4).

3 Modelling Q0957+561

We developed a numerical code based on the standard gravitational lens equation to explain the absence of the double-peaked line profile towards CO−B in Q0957+561. The code has been applied on 6 different models of Q0957+561, all based on previous work by Barkana et al. (1999). They can be mainly divided into 2 main groups: one set of models is based on a King profiles, as proposed by Falco et al. (1985− models: FGS, FGSE, FGSE+CL), the second set on a softened power-law distribution, as suggested by Grogin et al. (1996−models: SPLS, SPEMD, SPEMD+CL). Each of these two sets can be subdivided into three subgroups assuming either elliptical or spherical profiles and/or a shear term or a Single Isothermal Sphere for the surrounding cluster. Besides the sizes of the lensed images, the positions, continuum and the blueshifted line intensity ratios, also the optical time delay (Kundic et al. 1997) has been taken into account to distinguish among the models. For simplicity, the respective components were simulated as slightly extended gaussians. The SPEMD+CL and FGSE+CL models reproduce the observed constraints with the lowest χ_r^2 (≤ 3) showing that the contribution of the cluster is important: The models that best explain these observations all require a SIS cluster.

Line emission: Let us first forget about the redshifted CO-A component and concentrate on the blueshifted line. A compact region centered on the nucleus can be directly ruled out by the small line ratio B-blue/A-blue of 0.4 since this would be in contradiction with the measured 3mm continuum ratio A/B of 1.5 originating in a compact region. An extended region of the blueshifted line indeed reproduces the derived small line ratio of 0.4 but it would have a particular shape (very extended in direction of the nuclear jet ($\sim$ 5") but very thin perpendicular to it). Also a non-nuclear position of the blueshifted emission region with a rather compact shape and closer to the inner tangential caustic originates in a small line ratio.

The difference in the line profiles observed towards CO$-$A and CO$-$B can be explained by the location of the redshifted gas component relative to the lens caustic. In the best-fit simulation for the SPEMD+CL model the two caustics are so close together that the blueshifted component of Q0957+561 is still located between them whereas the redshifted line must originate above the northern outer caustic. This calculation used two separated components of the red- and blueshifted line but we can also start with an extended region centered on the nucleus where the north-eastern part corresponds to the redshifted component and the south-western part to blueshifted one. The morphology that reproduces the derived line ratio (A-blue+A-red)/B-Blue$\sim$ 1.1 agrees well with the model of the host galaxy used by Keeton et al. for the Barkana FGSE+CL model being quite close to our best-fit FGSE+CL model.

4 Discussion and Conclusions

What can we conclude about the origin of the redshifted CO(2-1) velocity component? Mainly two groups of hypotheses are possible: it either originates from an independent system (companion etc.) or traces the presence of molecular gas in the rotating disk of the host galaxy in Q0957+561. We have reasons to discard the first class of hypotheses. One of the strongest arguments is that the host galaxy detected in HST observations by Keeton et al. (2000) is oriented in the direction of the two line components in CO$-$A and is extended on the same scale. Also the integrated line ratio of (CO-A-red+CO-A-blue)/CO-B $\approx$1.0 is consistent with Keeton et al. (2000). Furthermore, the simulation of the two velocity profiles together supports also an extended disk similar in shape to the used host galaxy models of Keeton et al. 2000 whereas the model for a single blueshifted component would either suggests a very thin but very elongated disk not at all similar to the host galaxy detected in the optical or a quite compact CO region offset from the nucleus. The redshift of this region would then also be significantly different from the one of the host galaxy and the quasar. Thus, the latter two approaches seem to be quite unlikely compared to Keeton et al.'s (2000) results for the host galaxy. Furthermore, the double-peaked line profile at CO$-$A

appears to be symmetric and is centered within the errors at $z_0 = 1.4141$. Based on these arguments, we favour the second hypothesis: the presence of an important reservoir of molecular gas in a disk of the host galaxy surrounding Q0957+561. Based on the lower magnification from the FGSE+CL model, we have estimated an upper limit to the molecular gas mass for each integrated blue and redshifted velocity profile in CO−A and CO−B. Assuming a standard M_{gas} to $L'_{\mathrm{CO}(1-0)}$ ratio ($\simeq 5\,M_\odot(\mathrm{K\,km\,s^{-1}pc^2})^{-1}$, Downes et al. 1993) and R_{21} =CO(2-1)/CO(1-0)$\lesssim$1, we find $M_{\mathrm{gas}} = 2.3 \times 10^{10}\,M_\odot$ for both the blue and red velocity profiles. The low upper limit on $R_{54} \simeq 1$, the velocity averaged line ratio, characterizes low excitation conditions, and thus agrees with global CO emission from a disk. The agreement between molecular gas masses obtained with the integrated CO luminosities and individual magnification factors, each tracing line emission from half of the quasar host, is a further support for the rotating disk hypothesis.

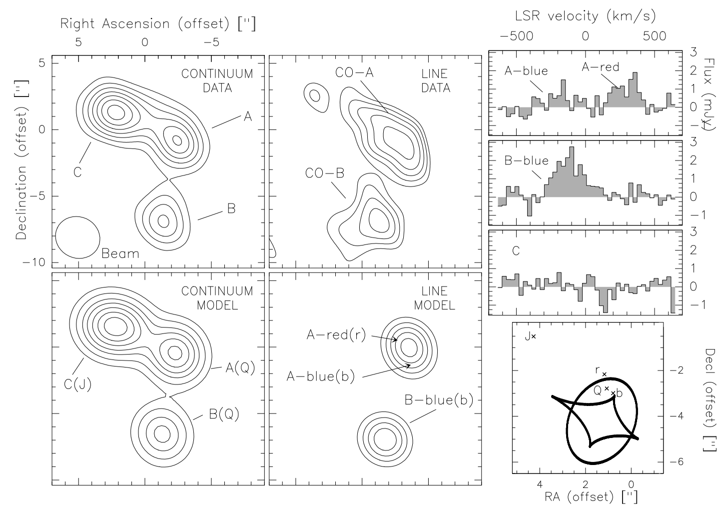

Fig. 1. Upper panel: observed continuum (left) & line emission (middle) plus spectrum (right); lower panel: simulated data with the lens plane (right).

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